Depth-Resolved MCD Studies of Magnetism at Buried Interfaces Using X-Ray Standing Waves

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INTRODUCTION

Interfaces between two phases and/or elements are of great interest because macroscopic properties of materials are often controlled by the microscopic details of how the transition in chemical, electronic and geometric arrangement of atoms is made across them [1-10]. Understanding how this transition is made across buried interfaces between condensed phases is both very important and tremendously difficult. The difficulty lies in depth-resolving properties of interest at buried interfaces, since most techniques involving electron or photon detection have depth sensitivity determined by exponential penetration or escape depths that provide only limited capabilities to resolve changes in depth over sub-nanometer length scales [11-13]. We are extending optical standing wave techniques [14] familiar at longer and shorter wavelengths into the 500 – 1000 eV range for the first time to study depth-resolved magnetic properties using magnetic circular dichroism (MCD) at $L_{2,3}$ edges for 3*d* transition metals and other x-ray magneto-optical techniques.

Magnetic properties of ultrathin films can be drastically altered by their interfaces. The broken symmetry and other aspects of disorder at surfaces or interfaces are thought to be responsible for these changed magnetic properties, through changes in local electronic structure that affect the local of magnetic moments and their orientations at the interface [1-10]. X-ray magnetic circular dichroism (MCD) has become an established tool to separate orbital (M_L) and spin (M_S) magnetic moments [4-8,11-13,15,16] through sum rules [17,18]. To understand surface and/or interface magnetism, there have been many measurements of M_L as a function of the thickness of magnetic layers [5,6]. However it is often overlooked in such measurements that the measured values of M_L are averaged over the entire thickness so that the signals from the interface region can be suppressed by those from the interior of the entire thickness as the Co layer becomes thick.

Our goal is to combine standard standing wave (SW) techniques with soft x-ray magneto-optical techniques to more directly probe magnetism at buried interfaces. This initial experiment combines standing waves with MCD to discriminate the magnetic response at interface region from the interior of the 20 Å thick Co layer in a designed structure of Pd(10 Å)/Co(20 Å)/Pd(20 Å) sandwich film having the in-plane magnetization.

EXPERIMENTS

A spatially varying optical SW is generated by a multilayer interference structure of $[B_4C(21.4\ \text{Å})/W(17.5\ \text{Å})]_{40}$ and extends into the region above the multilayer substrate. The magnetic trilayer system of interest is grown directly onto the multilayer standing wave generator (SWG), and the entire structure is designed so that the periodicity of the standing wave produced by the multilayer matches the dimensions of interest to probe in the Co film. Figure 1(A) shows the x-ray reflectivity of the SWG and trilayer/SWG structure, and reveals that the diffraction properties of the SWG are not destroyed by the trilayer. Figure 1(B) shows the calculated electric field intensity $E^2(z)$ in the trilayer using measured Co magneto-optical properties for opposite helicity. By varying incident angle around the first order Bragg peak of the SWG at a given photon energy, *hv*, the phase of SW is shifted by π with respect to the period. The structure is designed so that the strongest standing wave, occurring at the interference maximum of the SWG, has peak $E^2(z)$ near the bottom Co/Pd interface. This corresponds to scattering vector q = 0.17 for the present sandwich structure, where $q = 4\pi \sin\theta / \lambda_{x-ray}$ with grazing incidence angle θ.

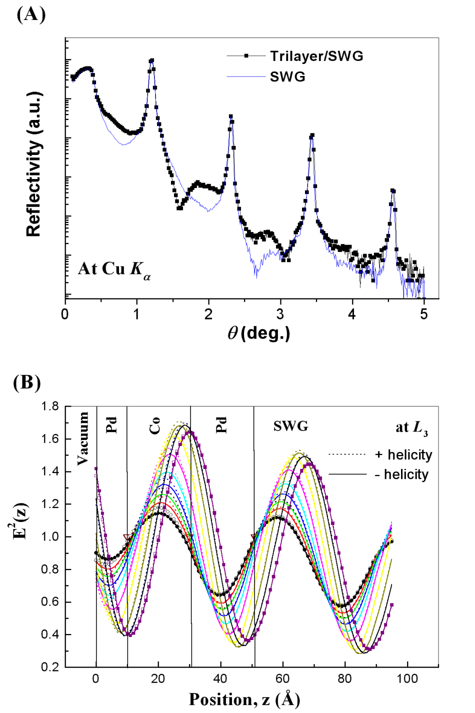

Figure 1. (A): x-ray reflectivities measured at x-ray tube Cu K_α. (B):Calculated intensity of SW from the over-structure of the sandwich film on the top of the interference multilayer structure based on the thickness parameters in text. +/- helicity dependent optical constants of Co L_3 edge measured from the present sample were used. Scattering vector, q is shown only ranging from 0.16 (circle) to 0.20 (square).

To investigate the SW enhanced MCD signals, we measured absorption through commonly used total electron yield (TEY) technique [5-7]. Measurements were made by scanning θ ranging from 10º to 15º (the Bragg peak remains within this range for all *hv*) at fixed *hv*, ranging from 764 to 814 eV using left circularly polarized x-rays with the degree of circular polarization of 0.76 as measured with our polarimeter. Reference absorption spectra were collected as a function of *hv* at θ=10° to correct for experimental asymmetries in the θ-scans in the presence of magnetic field. The absorption spectra measured at θ=10° corresponding to an average over the entire thickness of Co layer are not sensitive to the layer position other than through standard escape depth considerations. Spectra were all recorded at an external magnetic field of about 1 kOe, which is greater than the in-plane coercivity of the sample, whose remenant magnetization almost equals the saturation value. This applied field was essentially parallel to the x-ray propagation direction, and was reversed to obtain MCD absorption data with fixed photon helicity. Data were collected on bending magnet beamline 9.3.2.

RESULTS

Figure 2 shows all θ-scans as a function of *hv* for +/- helicity, renormalized by reference absorption spectra of the corresponding helicity measured at θ=10°. These data are plotted as a $q - hv$ surface because the standing wave position occurs at fixed q for all *hv*. Since photoelectron yield is much larger than fluorescence signal in soft x-ray ranges, TEY is used in this study even though this mode cannot exclude the contribution from the top and bottom Pd layers, and SWG itself. According to the typical effective electron escape depth of λ_{eff} [5,12,13], the absorption of the SWG does not contribute to the measured signal. The SW resonance at both pre- and post-edges shown in Figure 2 are thus due to the photoelectron contribution from the top and bottom Pd layers.

Data analysis requires careful normalization of the surfaces in Figure 2 to a per Co atom scale to remove the Pd background contribution to obtain the standing wave enhanced absorption of only the Co. This analysis requires detailed consideration of $E^2(z, h\nu, q)$, i.e., how the electric field intensity varies not only in depth but also as functions of photon energy and incidence angle. First an appropriately normalized Pd contribution is subtracted, and then the resulting Co signal is normalized. Calculations of this full $E^2(z, h\nu, q)$ are required in this process, in turn requiring reliable values for the optical properties of both the SWG and trilayer components. We find that generally the $h\nu$ dependence of normalization corrections is much less than the q dependence, because the SWG contains no Co and the 20 Å Co layer is a relatively small optical perturbation to the standing wave field. With care reliable depth sensitive absorption coefficients $\overline{\mu}_{+/-}^{Co}$ weighted by $E^2(z)$ at each q can be obtained, from which polarization averaged and difference (MCD) spectra can be obtained.

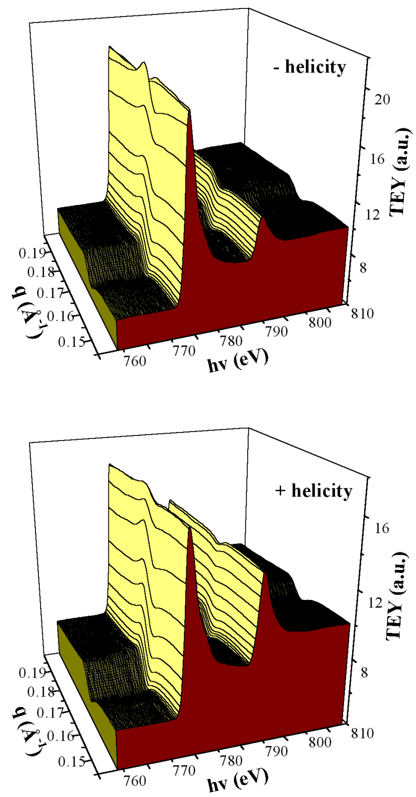

Figure 2. All angle scans as function of $h\nu$ renormalized to the corresponding absorption spectra measured at θ=10 °, converted into q-$h\nu$ surface.

The magnetic moments are related to the spin and orbital moments by $M_L = -\mu_B L$ and $M_S = -2\mu_B S$, where L and S are the expectation values of orbital and spin moments along the magnetization direction. μ_B is the Bohr magnetron. The sum rules [17,18] relate these L and S moments with the integrated area at the corresponding edges in the difference and the sum of +/- absorption spectra. Accordingly, this standing wave technique allows the spatial variation of these properties as a function of position at buried interfaces which was reported for the first time [19]. Further details of the analysis, results including depth-resolved changes in the number of d holes, orbital and effective spin moments, and interpretation will be presented elsewhere [20].

The standing wave technique demonstrated here will be useful to study various other problems and systems where depth-resolved information at buried interfaces is crucial.

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REFERENCES

[1] J. G. Gay and R. Richer, Phys. Rev. **B** 56, 2728 (1986).
[2] P. Bruno, Phys. Rev. **B** 39, 865 (1989).

[3] G. H. O. Daalderop, P. J. Kelly, and M. F. H. Schuurmans, Phys. Rev. B **44**, 12054 (1991).
[4] J. Stöhr and H. Konig, Phys.Rev. Lett. **75**, 3748 (1995).
[5] M. Tisher, O. Hjortstam, D. Arvanitis, J. Hunter Dunn, F. May, K. Baberschke, J. Trygg, J. M. Wills, B. Johansson, and O. Eriksson, Phys. Rev. Lett. **75**, 1602 (1995).
[6] D. Weller, J. Stöhr, R. Nakajima, A. Carl, M. G. Samant, C. Chappert, R. Megy, P. Beauvillain, P. Veillet, and G. A. Held, Phys. Rev. Lett. **75**, 3752 (1995).
[7] H. A. Dürr, G. Y. Guo, G. van der Laan, J. Lee, G. Lauhoff, and J. A. C. Bland Science **277,** 213 (1997).
[8] G. van der Laan, Phys Rev. **B 57**, 5250 (1998); Phys. Rev. Lett. **82**, 640 (1999).
[9] S.-K. Kim, V. A. Chernov, Y. M. Koo, J. Mag. Mag. Mater. 170, **L7**, (1997).
[10] S-K. Kim, V. A. Chernov, J. B. Kortright, and Y. M. Koo, Appl. Phys. Lett. **71**, 66 (1997).
[11] C. T. Chen, Y. U. Idzerda, H.-J. Lin, N. V. Smith, G. Meigs, E. Chaban, G. H. Ho, E. Pellegrin, and F. Sette, Phys. Rev. Lett. **75**, 152 (1995).
[12] W. L. O'Brien and B. P. Tonner, Phsy. Rev. B **50**, 12 672 (1994).
[13] V. Chakarian, Y. U. Idzerda, and C. T. Chen, Phys. Rev. **B 57**, 5312 (1998).
[14] B. W. Batterman, Phys. Rev. Lett. **22**, 703 (1969).
[15] Y. Wu , J. Stöhr, B. D. hermsmeier, M. G. Samant, and D. Weller, Phys. Rev. Lett**. 69**, 2307 (1992).
[16] R. Wu, D. Wang, and A. J. Freeman, Phys. Rev. Lett. **71**, 3581 (1993).;R. Wu and A. J. Freeman, Phys. Rev. Lett., **73**, 1994.
[17] T. Thole, P. Carra, F. Sette, G. van der Laan, Phys Rev. Lett. **68**, 1943 (1992).
[18] P. Carra, B. T. Thole, M. Altarelli, and X. Wang, Phys. Rev. Lett. **70**, 694 (1993).
[19] S.-K. Kim and J. B. Kortright , presented at the 43th Annual Conferece on Magnetism and Magnetic Materials, 9-12 November, 1998, Miami, FL, USA
[20] S.-K. Kim and J. B. Kortright, (to be published).

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